Soil organic carbon dynamics as related to land use history in the northwestern Great Plains

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[1] Strategies for mitigating the global greenhouse effect must account for soil organic carbon (SOC) dynamics at both spatial and temporal scales, which is usually challenging owing to limitations in data and approach. This study was conducted to characterize the SOC dynamics associated with land use change history in the northwestern Great Plains ecoregion. A sampling framework (40 sample blocks of 10 $\times$ 10 km^2 randomly located in the ecoregion) and the General Ensemble Biogeochemical Modeling System (GEMS) were used to quantify the spatial and temporal variability in the SOC stock from 1972 to 2001. Results indicate that C source and sink areas coexisted within the ecoregion, and the SOC stock in the upper 20-cm depth increased by 3.93 Mg ha^{-1} over the 29 years. About 17.5% of the area was evaluated as a C source at 122 kg C ha^{-1} yr^{-1}. The spatial variability of SOC stock was attributed to the dynamics of both slow and passive fractions, while the temporal variation depended on the slow fraction only. The SOC change at the block scale was positively related to either grassland proportion or negatively related to cropland proportion. We concluded that the slow C pool determined whether soils behaved as sources or sinks of atmospheric CO_2, but the strength depended on antecedent SOC contents, land cover type, and land use change history in the ecoregion.

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1. Introduction

[2] Temporal changes in soil organic carbon (SOC) stock are more informative than absolute quantities for evaluating the potential of terrestrial ecosystems to offset a portion of the CO_2 emissions from human activities. Temporal variations in SOC stock can be used to infer changes in fundamental properties of ecosystems that result from either land use or management practices. Measurements of SOC temporal changes are needed to understand net C exchange between terrestrial ecosystems and the atmosphere over large areas. It has also been recognized that the CO_2 mitigation strategies based on terrestrial C sequestration must involve large areas as one condition for atmospheric CO_2 removal that can exceed the carbon (C) emission from plants and soils [*Ellert et al.*, 2002]. The spatial variation of SOC is a function of a set of factors such as relief, parent material, climate, plant cover, anthropogenic activities, and time [*Jenny*, 1980]. The C sequestration potential of ecoregions can be assessed by integrating and aggregating spatial data characterizing these factors (e.g., soil properties, land use or land cover, and climatic regime) and their temporal variations.

[3] In the last decade, many biogeochemical models have been developed to simulate C cycles at various spatial scales. Process-based modeling studies primarily have focused on potential vegetation conditions, with relatively static land use information, and few of them were capable of dynamically integrating land use change information into the simulation processes over large areas [*Chen et al.*, 2000; *Liu et al.*, 2004b]. In addition, applying ecosystem models at a very coarse spatial resolution would likely result in biases [*Turner et al.*, 2000; *Jenkins et al.*, 2001].

[4] The Intergovernmental Panel on Climate Change (IPCC) developed the Revised Guidelines for National Greenhouse Gas Inventories to provide methods for estimating emissions by sources and removal by sinks of greenhouse gases [*Houghton et al.*, 1997], in which the Land Use and Land Use Change section provides a method to estimate average annual C sources or sinks from soils with changes in land use and management

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over a 20-year inventory period. Default values for baseline SOC pools are provided along with a series of coefficients that determine C pool changes as a function of climate, soil type, disturbance history, tillage intensity, productivity, and residue management. Though the IPCC Good Practice Guidance for Land Use, Land-Use Change and Forestry was recently developed to improve the uncertainty estimates of emissions by sources and removal by sinks of greenhouse gases [*Penman et al.*, 2003], it is difficult to directly quantify the level of uncertainty in this type of analysis because each input data set has an associated level of uncertainty through the analysis [*Cannell et al.*, 1999; *Houghton et al.*, 1999]. The uncertainty in the estimates of GHG emissions or reduction with land use change may be as high as 50% [*Houghton et al.*, 1997].

[5] Recently, the General Ensemble Biogeochemical Modeling System (GEMS) has been developed by *Liu et al.* [2004a, 2004b] to integrate spatially and temporally explicit information (especially land use change over time) into process-based biogeochemical modeling at a regional or a national scale. This model has been successfully applied to characterize the impacts of land cover changes on the contemporary C sources and sinks over the last 3 decades in the southeastern plains of the United States. Briefly, GEMS uses a Monte-Carlo based ensemble approach to incorporate the variability (as measured by variances and covariance) of the state and driving variables of the underlying biogeochemical models into simulations. Thus GEMS simulates not only the spatial and temporal trends of C dynamics such as C exchange between the terrestrial biosphere and the atmosphere, but also provides uncertainty estimates of the predicted variables in time and space [*Liu et al.*, 2004b].

[6] Most investigations of terrestrial C dynamics have focused on the estimation of C sequestration potential with either given land use changes or improved management practices from point observations (or paired experimental sites), then extrapolated these results to a regional or a national scale with some assumptions. Terrestrial ecosystems, however, are diverse with multiple land uses or land covers that reflect the patterns of natural resources, socioeconomic conditions, and settlement history. This diversity must be accounted for in forecasted SOC changes under conservation scenarios proposed for target land cover types. Realistically, we need to know present SOC stocks, past land use history, and future land use changes for the entire ecosystems rather than for a single sector. Therefore this study was conducted to simulate the time-dependent SOC change in the northwestern Great Plains using GEMS.

[7] The work reported here is an integral part of the Contemporary U.S. Carbon Trends project, which has three specific aims [*Liu et al.*, 2004b]: (1) characterizing terrestrial C pools within sample blocks using a sampling framework rather than a conventional wall-to-wall approach, (2) detecting land use change using remotely sensed data at both a high temporal sampling frequency and a high spatial resolution, and (3) simulating C dynamics within each sample block by specifying the variance and covariance of major input variables using GEMS.

2. Materials and Methods

2.1. Study Area

[8] The study area is the northwestern Great Plains, or ecoregion 43, one of the 84 Omernik level III ecoregions [*Omernik*, 1987] (42°31′05″N–48°14′14″N, 99°00′51″W–111°59′45″W). Its total surface area is about 338,718 km^2. It covers western South Dakota, southwestern North Dakota, southeastern Montana, and northeastern Wyoming (Figure 1). The ecoregion is largely an unglaciated, semiarid rolling plain of shale and sandstone. It is punctuated by occasional buttes and badlands, with ephemeral-intermittent streams and a few perennial rivers. The annual average precipitation from 1971 to 2000 was 401 ± 51 mm, and the annual average temperature was 7.1 ± 1.1°C with a frost-free period from 75 to 143 days. The climate in the northwestern Great Plains is characterized by an east-west precipitation gradient (wetter in the east) and a south-north temperature gradient (warmer in the south).

[9] The ecoregion is vegetated by mixed-grass prairie in Montana and the western Dakotas, and shortgrass prairie in Wyoming [*Biondini et al.*, 1998]. Native grasslands persist on broken topography where they are used for livestock grazing and wildlife habitat, but were largely replaced on level ground by spring wheat (*Triticum aestivum*) and alfalfa (*Medicago sativa*). Agriculture is usually limited by the erratic precipitation and the scarce water resources for irrigation [*Omernik*, 1987].

2.2. Data Sources

[10] This study primarily used three categories of model inputs: climate, land use/cover, and soil survey. Climate data from 1970 through 2000 included monthly averages of precipitation and temperature for each sample block. They were adapted from *Climate Research Unit* (available at http://www.cru.uea.ac.uk/cru/data/hrg.htm). Initial soil characteristics within these sample blocks were based on the U.S. State Soil Geographic Database (STATSGO) [*U.S. Department of Agriculture Natural Resources Conservation Service*, 1994]. STATSGO data were used to initialize the soil components of GEMS. In GEMS, a soil component was randomly picked for a specific stochastic simulation from all components within a soil map unit in proportion to the component's area in the sample block [*Liu et al.*, 2004b]. The larger the area of a soil component, the more likely it was to be selected as the basis for a specific model simulation. Once the component was determined, soil characteristics such as drainage class, soil texture, high and low values of soil organic matter (SOM) content (converted to SOC using a factor of 0.58), soil bulk density, and water-holding capacity were retrieved from the corresponding soil component and layer attribute tables.

2.3. Sampling Protocol and Land Use Information Abstraction

[11] Detailed wall-to-wall simulations of terrestrial C dynamics across the conterminous United States are possi-

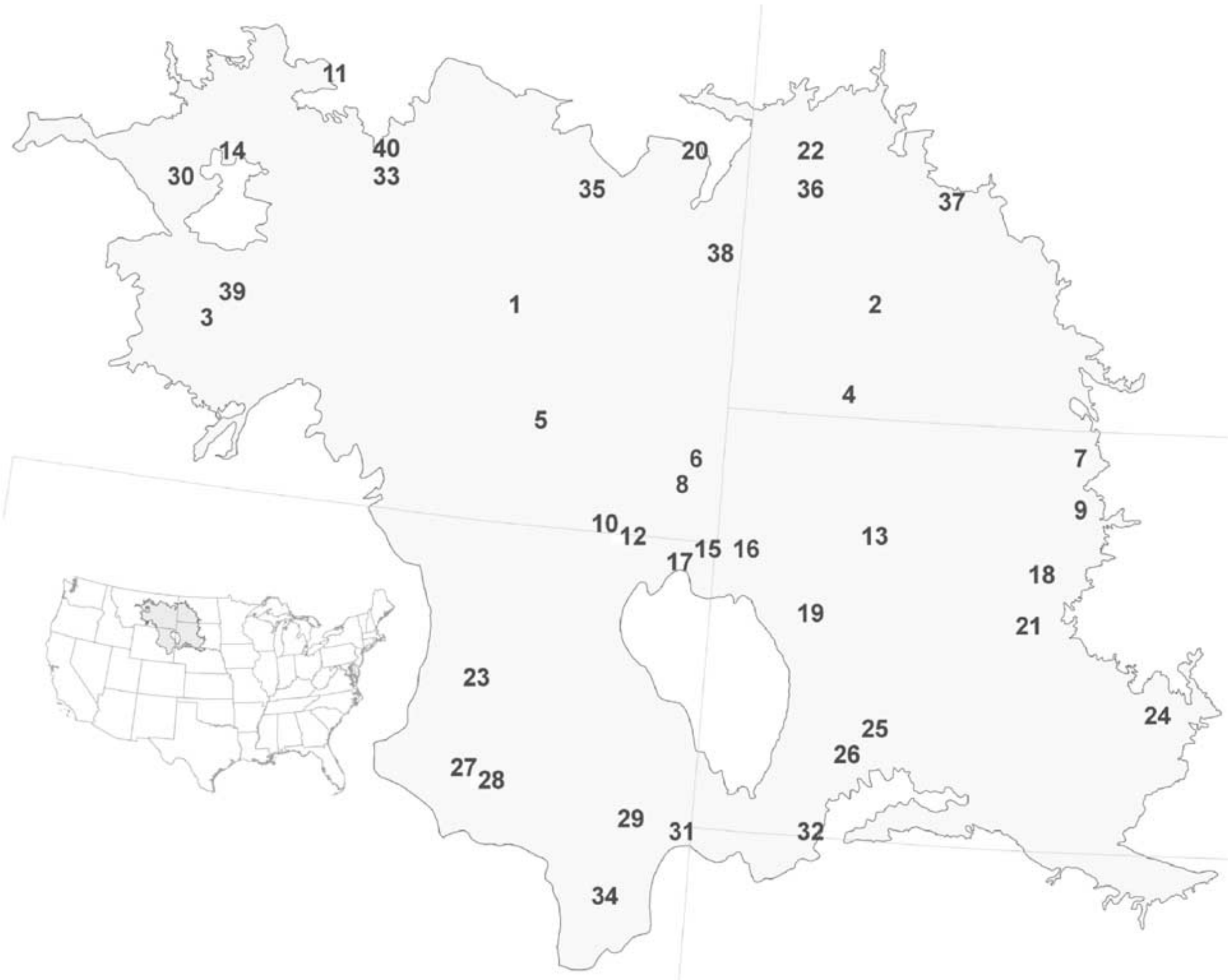

Figure 1. Study area and sample block locations in the northwestern Great Plains ecoregion. See color version of this figure at back of this issue.

ble but have not been undertaken because consistent high-resolution land use change databases have not been available [*Liu et al.*, 2004b]. Therefore the sampling framework proposed by *Loveland et al.* [2002] was introduced to identify the spatial variation of land cover change. Forty sample blocks of 10 km × 10 km were randomly selected within the ecoregion to identify changes with 1% precision at an 85% confidence level. The changes were detected based on five dates of Landsat Multispectral Scanner (MSS) and Thermatic Mapper (TM) imagery data for 1973, 1980, 1986, 1992, and 2000 that were analyzed at a cell size of 60 m × 60 m for Landsat MSS images and 30 m × 30 m for TM images.

2.4. Model Simulations

[12] The structure and functions of GEMS have been described by *Liu et al.* [2004a, 2004b]. GEMS consists of three major components: one or multiple encapsulated ecosystem biogeochemical models, a data assimilation system (DAS), and an input/output processor (IOP). The DAS consists of data search/retrieval algorithms and data processing mechanisms. The data search/retrieval algorithms are responsible for searching and retrieving relevant information from various databases according to the keys provided by a joint frequency distribution (JFD) table [*Reiners et al.*, 2002; *Liu et al.*, 2004a], while data processing mechanisms downscale the information that was aggregated from individual map units to the field scale using a Monte Carlo approach. Once data are assimilated, they are incorporated into the modeling processes by means of the input/output processor to update the default input files with assimilated data. Values of selected output variables are also written by the IOP to a set of output files after each model execution. The JFD grids were first created from a time series of land cover maps (i.e., land covers in 1973, 1980, 1986, 1992, and 2000), soil, and climate themes at a cell size of 60 m × 60 m. In this study, a total of 1696 unique combinations of these variables (mainly in terms of both land cover category and soil map units) were generated with a frequency ranging from 1 to 27889 grid cells. Each

Table 1. Dominant Land Cover Conversions and Change Rates Between 1973 and 2000 in the Northwestern Great Plains[a]

Conversion	1973 to 1980, %	1980 to 1986, %	1986 to 1992, %	1992 to 2000, %	1973 to 2000	
					Area, km^2	Percent
Grass/shrub to ag	0.93	0.92	2.25	1.56	18,032	5.32
Ag to grass/shrub	0.67	0.85	0.33	0.79	10,080	2.98
N. trans to forest	0.41				1390	0.41
Water to grass/shrub	0.06		0.20		913	0.27
Grass/shrub to water		0.09		0.09	608	0.18
Water to wetland			0.14		484	0.14
Barren to water		0.06		0.07	437	0.13
Total change, %	2.07	1.92	2.92	2.51	31,944	9.43

[a]Land cover change rates are the percents of the total surface area of this region for respective time intervals; the total area of the region is about 338,718 km^2, and all numbers in the table were derived from the data provided by the USGS Land Cover Trends Project team, USGS National Center for EROS.

sample block contained about 42 unique combinations on average, varying from 8 to 166 combinations.

2.5. Data Analysis and Presentation

[13] We used sample blocks as data aggregation units, and analyzed them in time series from 1972 through 2001 (encompassing the official Land Cover Trends' period set from 1973 through 2000 with a 1-year buffer before and after). SOC stock was defined as the total SOC storage in the 0–20 cm depth of soil and expressed in Mg C ha^{-1}. The SOC change was determined as the difference in SOC stocks between 2001 and 1972. The term "C sink- or source strength" was used to indicate the extent of soil C sequestration or depletion for a specific time span, and was expressed in kg C ha^{-1} yr^{-1}. The results were generally expressed by the mean ± stderr (standard error), otherwise specified. To minimize the influences of other large land covers such as forest and water body, only sample blocks with combined areal percentages of both grassland and cropland greater than 85% or forest cover percentages less than 12% were selected for analyzing the effects of land cover on SOC changes between 1972 and 2001. The spatial variations and change in SOC stocks were analyzed using Kriging interpolation models supported by ArcGIS 9.0 [*Environmental Systems Research Institute*, 2004].

3. Results and Discussion

3.1. Land Cover Change Trends From 1973 to 2000

[14] Both grass/shrub cover and agricultural land use were prevalent in the northwestern Great Plains ecoregion between 1973 and 2000. The cumulative area of grass/shrub cover (hereinafter called grassland) increased from 74.9% to 77.1%, and the cumulative area of cropland decreased from 17.2% to 15.4%. The percentage of wetland increased from 0.18% in 1973 to 0.26% in 2000. Almost no changes in other land covers were observed during this period. The changes in all land cover categories in the ecoregion have taken place at an annual average rate of 0.35% between 1973 and 2000 (Table 1). The spatial variation and temporal change trends of land cover for selected sample blocks are illustrated in Figure 2.

[15] There was a substantial expansion of cropland before the mid-1980s (data are available at http://www.nass.usda.gov/QuickStats/) followed by implementation of the Conservation Reserve Program (CRP) after Congress passed the Food Security Act in 1985 (data are available at http://www.fsa.usda.gov/dafp/cepd/default.htm/). During the last 2 decades, about 1.9 Mha of cropland were converted to CRP grasslands, and the fallow area was increased by 9.7% in Montana, North Dakota, South Dakota, and Wyoming (data are available at http://www.nrcs.usda.gov/technical/NRI/1997/summary_report/table3.html/). These spatial and temporal changes in land cover in the last 3 decades have certainly exerted substantial impacts on the SOC dynamics and modified the C source-sink relationships in the terrestrial ecosystems.

3.2. Historical Soil Organic C Stocks

[16] The SOC stock simulated by GEMS for any specific time varied substantially from sample block to sample block, ranging from 24.3 ± 2.5 to 85.1 ± 2.2 Mg C ha^{-1}, and generally increased along the southwest to the northeast precipitation gradient (Figures 3a and 3b). The spatial variation in SOC stock was significant (coefficient of variation (CV) = 28.6%). The average SOC stock of the entire ecoregion increased from 46.9 Mg C ha^{-1} in 1972 to 50.8 Mg C ha^{-1} in 2001, increasing by 8.3% over the 29-year period with a CV of 2.6%. The spatial distribution patterns of SOC stock (Figures 3a and 3b) generally coincided with the distribution patterns of NPP magnitudes averaged from 1972 to 2001 (Figure 3c), suggesting that higher biomass production has led to more C input into soil. These spatial distribution patterns are also in agreement with the historical levels of grassland productivity and SOM levels that vary along the orientations of precipitation and temperature gradients [*Jenny*, 1980; *Schimel et al.*, 1990; *Peterson and Cole*, 1995].

3.3. Soil Organic C Change and Source-Sink Strengths

[17] The simulated increase in SOC stock between 1972 (the baseline) and 2001 was 3.93 Mg C ha^{-1} averaged for the whole ecoregion, or an annual accumulation average rate of 136 ± 24 kg C ha^{-1} yr^{-1}. However, seven of the 40 sample blocks (numbered 2, 4, 11, 22, 34, 37 and 38 in Figure 1) were significant C sources, emitting an average of 127 kg C ha^{-1} yr^{-1} in the same period. The spatial patterns

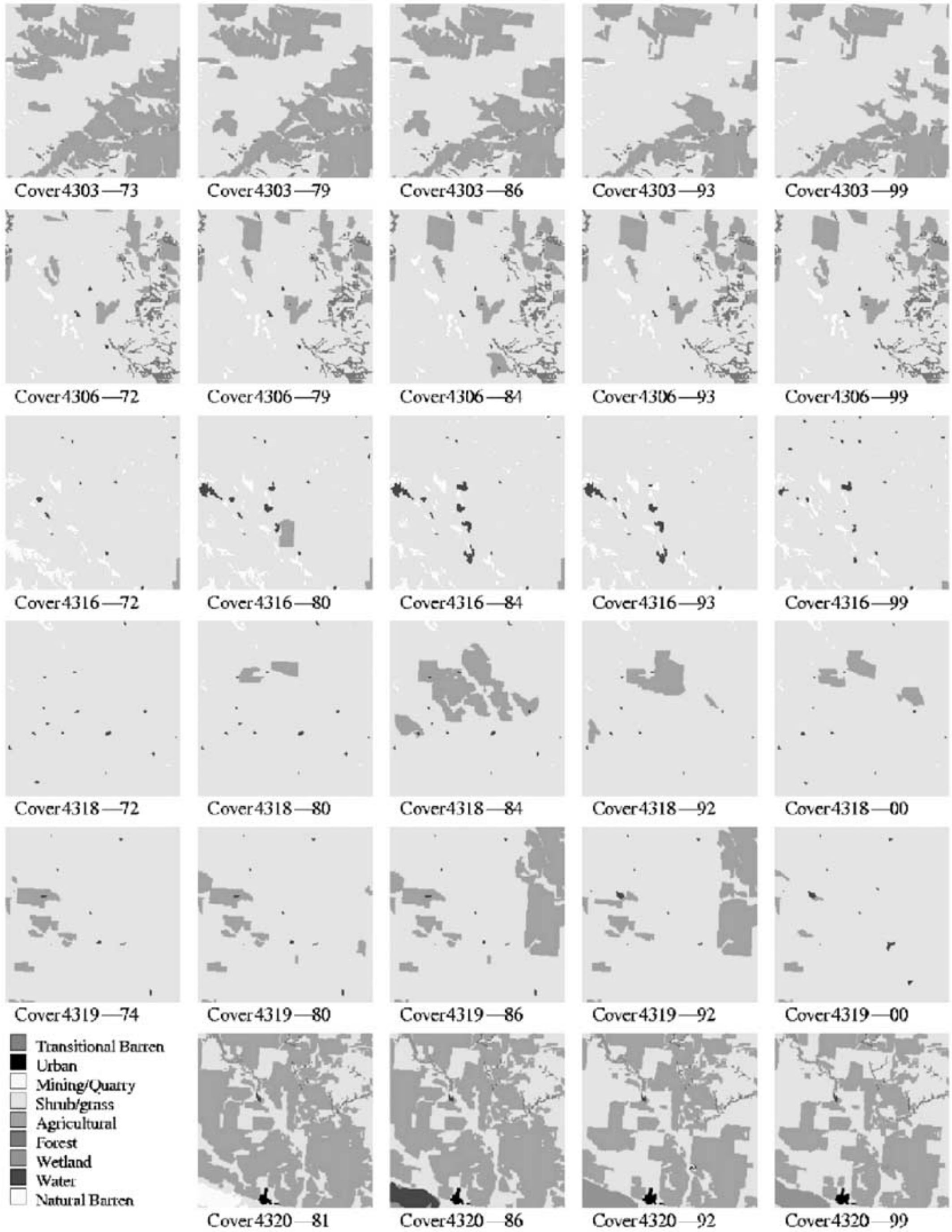

Figure 2. Spatial distribution patterns and temporal change trends for selected sample blocks (provided by the USGS Land Cover Trends Project team). Numbers below blocks denote block ID and year of imagery. See color version of this figure at back of this issue.

of C sources or sinks are illustrated in Figure 3d. Compared with spatial distribution patterns of the SOC stock in 1972, larger C increases over time generally corresponded to locations with lower SOC contents. The SOC sources (i.e., negative values in Figure 3d) appeared to be associated with the soils having high C stocks and the blocks dominated by cropland use.

[18] An expansion of cropland coupled with conventional tillage led to a significant SOC loss from disturbed soils, particularly prior to 1972 [*Donigian et al.*, 1994]. The land

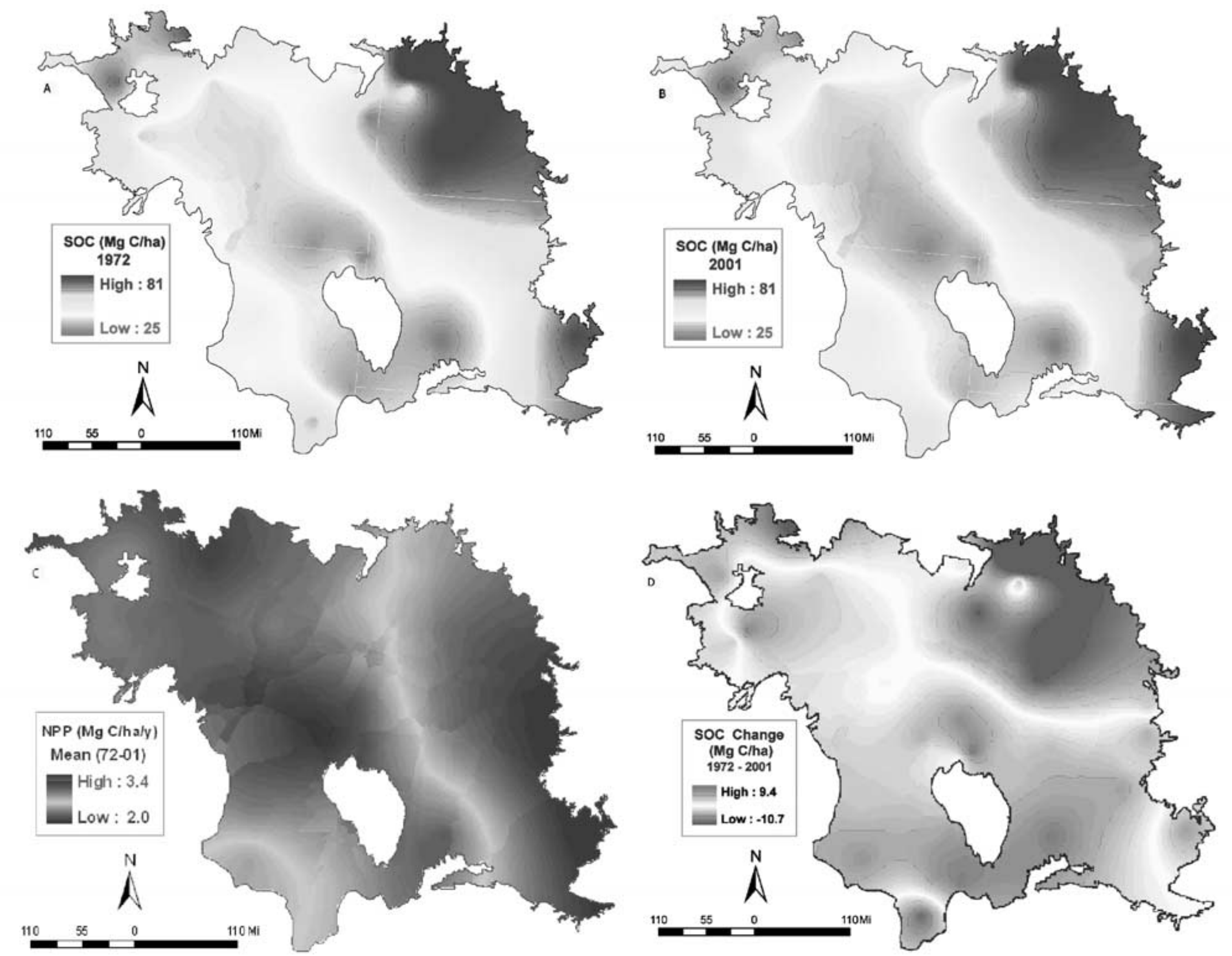

Figure 3. Spatial distribution patterns of SOC stocks, NPP, and SOC change in the ecoregion between 1972 and 2001: (a, b) the spatial distributions of total SOC stocks in 1972 and 2001, respectively; (c) the annual average net primary production (NPP) between 1972 and 2001; and (d) the change in SOC stocks from 1972 to 2001, and positive values indicate an increase in SOC stocks over this period). See color version of this figure at back of this issue.

use change history indicates that there was a trend of reduced tillage in the 1970s and widespread adoption of no-tillage and CRP since 1986 in the study area. Therefore we divided the span from 1972 to 2001 into two time intervals: 1972 to 1986 and 1986 to 2001. The SOC stocks as of 1972 and 1986 were considered as the respective baseline values for these two time intervals to calculate the strength of C sinks or sources. The relationships between the strength and baseline SOC stock can be generally described by quadratic models as illustrated in Figure 4, but the extent to which the baseline SOC affected the strength of C sinks or sources was also differentiated by time intervals, which reflected temporal changes in land cover and probably management. In the period from 1972 to 1986, nine sample blocks were a C source of 172 kg C ha^{-1} yr^{-1} from soil even though the ecoregion as a whole had been an overall C sink at 101 kg C ha^{-1} yr^{-1}. Between 1986 and 2001, only 5 sample blocks were C sources, with smaller C source strengths (60 ± 14 kg C ha^{-1} yr^{-1}) than in the previous period, and the C sink strength across the whole ecoregion increased to 168 kg C ha^{-1} yr^{-1}, ranging from 31 to 378 kg C ha^{-1} yr^{-1}. Figure 4 suggests that the soils with lower antecedent SOC contents likely have higher C sink strengths. The soils with higher C contents (>60 Mg ha^{-1}) are more likely to become C sources. Similar observations have been reported for cropping ecosystems in the northcentral United States [*Tan and Lal*, 2005].

3.4. Soil Organic C Temporal Trends Associated With Land Cover Change History

3.4.1. In Relation to Land Cover Category

[19] The data presented in Figure 5 show that the SOC change (either a source or a sink) between 1972 and 2001 was highly related to the proportion of grass cover or cropland area. For sample blocks whose areal portions of combined grass and crop covers were greater than 85% or

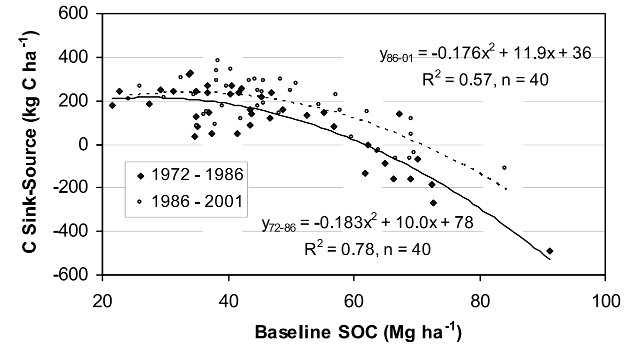

Figure 4. Effects of antecedent SOC stocks on C sink or source strengths (values <0 at *y* axis refer to C sources): the SOC stock in 1972 as the baseline for the period from 1972 to 1986 and the SOC stock in 1986 as the baseline for the period from 1986 to 2001.

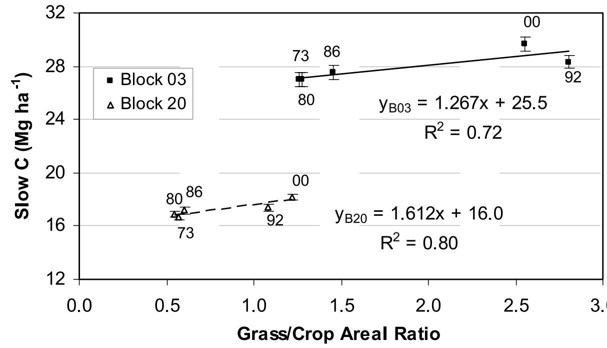

Figure 6. Temporal variations of slow C pools in relation to areal ratios of grass cover against cropped area. An integer number surrounding each point symbols refers to the calendar year. Error bars represent standard errors. Average standard error is 0.5 for block 03 and 0.2 for block 20. Both passive and labile fractions were not plotted here because they showed little sensitivity to land cover change.

forest cover less than 12%, the magnitude of the SOC change for the study period was positively related to the areal proportion of grassland (R^2 = 0.75, n = 34), or negatively related to the areal proportion of cropland (R^2 = 0.74, n = 34), with both relationships statistically significant. For example, sample blocks 2, 4, 22, and 30, where areal percentages of cropland were greater than 50%, experienced significant SOC depletion. These results suggest that C sinks likely occur in sample blocks dominated by grass cover, whereas C sources tend to occur in sample blocks with higher proportions of cropped area.

3.4.2. In Relation to Land Cover Change Rates

[20] To understand major forces driving C cycles in the ecosystems, we examined the land use history and its relation to the SOC change. Land cover change history was principally characterized by conversions between grass cover and cropped area, to which the slow C pool, owing to a shorter turnover time, is more sensitive than the passive pool. For sample blocks 3 and 20, we plotted the slow C pools against the areal ratios of grassland to cropland for the years of 1973, 1980, 1986, 1992, and 2000 (Figure 6). Slow C pools proportionally increased with decreasing cropped area as indicated by the positive slopes of the regressions. The rates of slow C accumulation depended more upon the baseline pool magnitudes than upon land cover change rates, even though the C dynamics were stimulated by land cover change. The direction of conversion between grassland and cropland determined whether a site was a sink or a source.

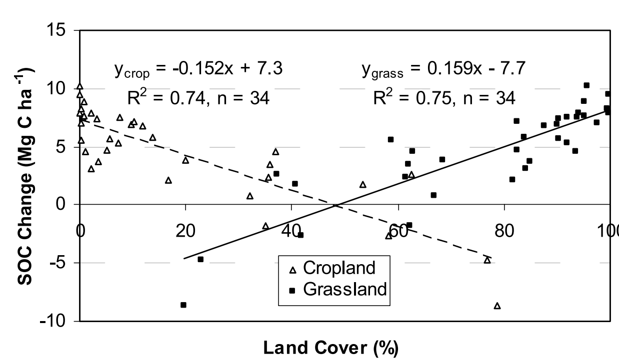

Figure 5. Magnitudes of C sources or sinks between 1972 and 2000 as related to proportions of cropland and grassland areas (sample blocks with areal percent of combined cropland and grassland <85% or forest cover >12% were removed). Note that each sample block is plotted twice: once in the cropland set and once in the grassland set.

[21] Figure 5 shows that 75% of all variance in the SOC change was associated with the areal proportion of either the grassland or cropland category in each sample block. As indicated in Table 1, the land cover change history in the study area was dominated by conversions between cultivated area and grassland cover, which should be one of the major driving factors controlling the SOC dynamics. By analyzing data cited from 23 observation sites worldwide, *Conant et al.* [2001] found an average SOC sequestration rate as high as 1010 kg C ha^{-1} yr^{-1} with conversion from cultivation to grassland. They attributed this huge C sink strength to prior soil C depletion following cultivation. *Ogle et al.* [2003] used the IPCC model to estimate change in SOC storage in all U.S. agricultural soils over the inventory period from 1982 to 1997. They found that SOC changes in the U.S. agricultural soils ranged from a loss of 4.4 Tg C yr^{-1}, mainly from managed organic soils, to a gain of 6.9 Tg C yr^{-1} from managed mineral soils. They attributed most of the uncertainty in estimates of either C sources or sinks not only to land cover conversions between cultivated and uncultivated conditions, but also to C losses from managed organic soils.

3.4.3. In Relation to the Conservation Reserve Program (CRP)

[22] According to the data provided by USDA Farm Service Agent (available at http://www.fsa.usda.gov/dafp/cepd/default.htm/), we can attribute the land cover change in the northwestern Great Plains ecoregion, to a great extent, to the extension of CRP, especially between 1986 and 2001. Of all land area of the ecoregion, the area registered for CRP increased from 0.05% in 1986 to

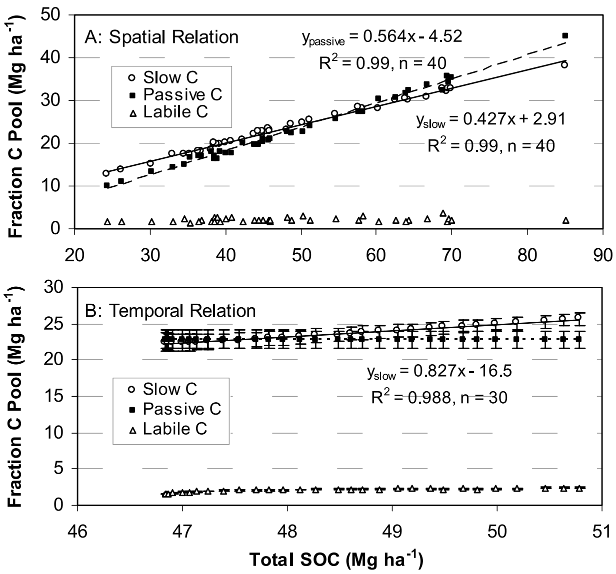

Figure 7. Dependence of total SOC stock on different fraction C pools. (a) Spatial variation indicated by 40 sample blocks in which each point is the block mean of all annual values between 1972 and 2001(standard error for slow, labile, and passive fractions are 0.20, 0.05, and 0.0, respectively). (b) Temporal variation indicated by 30 points in the chronosequence from 1972 through 2001 in which each point represents the annual mean of 40 sample blocks (standard error for slow, labile, and passive fractions are 0.95, 0.08, and 1.30, respectively).

3.02% in 1995. About 17% of cropped area was converted to CRP grassland in 1992 and 13% in 2001 in the ecoregion. *Collins et al.* [1999] pointed out that prairie-derived soils under conservation practices have a higher potential to sequester C than those derived from other land uses such as forests. On the basis of the paired observation data from 14 sites in the Great Plains and western Corn Belt, *Follett et al.* [2001] estimated an annual soil C sequestration rate (0–20 cm) of 910 kg C ha^{-1} yr^{-1} achievable on 10.6 Mha of CRP land. A regional application of the CENTURY model [*Parton et al.*, 1993] estimated a soil C sequestration rate of 600 kg C ha^{-1} yr^{-1} on CRP land across the Great Plains [*Paustian et al.*, 2001]. Using IPCC method and changing the IPCC Base Factor from agricultural land (0.7) to short-term set-aside land (0.8), *Eve et al.* [2002] estimated an annual increase in SOC of 460 kg C ha^{-1} yr^{-1} on CRP land in the northern plains. By evaluating factors responsible for the change in SOC storage in the U.S. agricultural soils between 1982 and 1997, *Ogle et al.* [2003] believed that most of the net C gain in mineral soils could be attributed to CRP. Therefore we also believe that CRP has enhanced C sinks in the northwestern Great Plains ecoregion between 1986 and 2001.

3.5. Dynamics of SOC Fractions in Association With Land Cover Category

[23] According to CENTURY Soil Organic Matter (SOM) model [*Parton et al.*, 1993], the SOC stock consists of three different C pools: passive, slow, and labile. They accounted for 47.0%, 48.7%, and 4.3% of the total SOC stock in the study area, respectively. As illustrated in Figure 7, the spatial variation in the SOC stock was highly correlated to both the slow and passive fractions and almost did nothing with the labile fraction (Figure 7a). The temporal variation in the SOC stock from 1972 through 2001 was almost exclusively contributed by the slow fraction pool (Figure 7b). In other words, the total SOC changes, either a sink or a source in the northwestern Great Plains, were the slow fraction-dependent. We understand that different models partition SOC into different conceptual pools [e.g., *Smith et al.*, 1997] and generate different temporal and spatial dynamics of SOC pools that are specific to respective models if they were applied in this study. However, the simulated overall trends of SOC dynamics in both space and time by any models should be similar to the results presented in this study as long as their performances are comparable to that of CENTURY.

[24] Organic matter fractions have differing resistance to microbial decomposition that is associated with specific protection mechanisms. Of all protection mechanisms, the physical protection through aggregation, which depends directly on land use type and management practice, plays a crucial role in fast turnover C fraction dynamics [*Jastrow and Miller*, 1998]. Figure 8a shows that the contribution of slow C pool to the total SOC stock in grassland soils increased in proportion to grass cover percentage in each sample block, whereas the reverse tendency was observed on cropland (Figure 8b). Grassland soils generally experience less disturbance and the

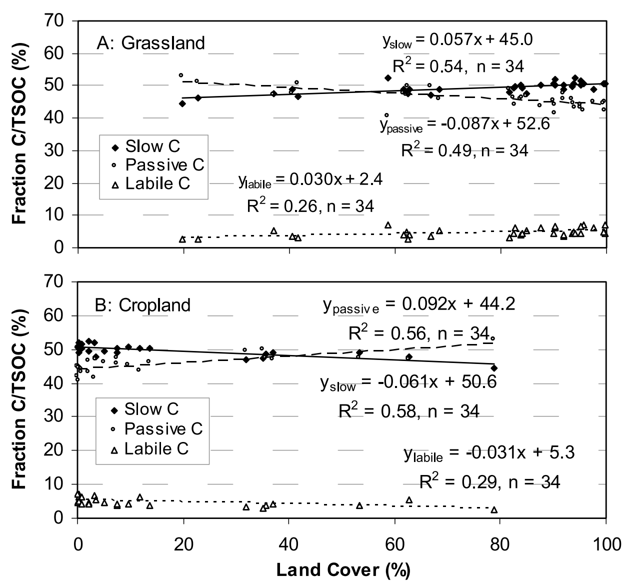

Figure 8. Variations in the proportion of each C pool to total SOC stock with change in land cover percentage. The sample blocks with areal percent of combined cropland and grassland <85% or forest cover >12% were removed.

entrapped fresh organic materials receive more physical protection. Conventional cultivation practices on croplands disturb the upper 20-cm depth of soil and enhance organic matter decomposition due to the breakdown of macroaggregates, whereas conservation measures such as no-till and CRP minimize soil disturbance and promote aggregation [*Jastrow et al.*, 1996; *Six and Jastrow*, 2002]. That the proportion of passive C pool in the total SOC stock decreased on cropland (Figure 8b) was mainly due to the depletion of the slow C fraction, because the pools of both passive and labile fractions did not show noticeable temporal variation over the 29-year span as illustrated in Figure 7B. *Studdert et al.* [1997] conducted a long-term crop-pasture (50:50 and 75:25) rotation experiments on one taxon of Mollisols (Argiudolls) in Balcarce, Argentina. They observed that the SOC content in 0–15 cm depth decreased by 11.8% in 6 to 7 years under cropping, and the lost C was almost composed of light-fraction. However, the lost SOC was recovered after 3 to 4 years of pasture usage. They attributed the recovery of SOC on pastureland to the increase in soil aggregate stability and the entrapped fresh organic matter. Mollisols are common in the northwestern Great Plains ecoregion, a similar effect might be expected there.

3.6. Uncertainty Analysis and Model Validation

[25] Uncertainties in model simulation are mainly resulted from initial values, inputs, model formulation, and validation data [*Klepper*, 1997]. GEMS simulates C dynamics in time and space by deploying the well-established CENTURY SOM model in space using the JFD of major driving variables of the C cycle [*Liu et al.*, 2004a, 2004b]. Uncertainties of the input data are propagated to simulated results through ensemble Monte Carlo simulations. As addressed previously, GEMS simulation was processed for each randomly picked-up combination (or case) of specific land cover and soil taxon with respective inputs retrieved from JFD files and each case was run 20 times to create outputs weighted by area proportion of cases with standard deviations. Therefore the inputs and outputs should have a better representation of the spatial and temporal heterogeneity of the driving variables than those based on the wall-to-wall simulation that ignores the spatial explicitness and covariance of these variables. Of course, the uncertainty of regional estimates depends on the number of sample blocks. Our results with standard errors indicate that forty 10-km by 10-km sample blocks in this ecoregion was enough to capture the general spatial and temporal variability of C stocks and fluxes. It is impossible to validate our modeling results using a few isolated point measurements. There are no dynamic regional-scale SOC databases to validate our simulated results because of multiple constraints at the state or ecoregion level. Fortunately, our simulated grain yields of major crops were in good agreement with the statewide mean values of grain yields provided by the USDA National Agricultural Statistical Service (data available at http://www.usda.gov/nass/) (e.g., corn yield was underestimated by 5% and spring wheat by 7%). The results presented in this paper should have represented the general patterns of SOC dynamics because of the stability and robustness of the GEMS-CENTURY model and the imposition of the multiple constraints.

4. Conclusions

[26] Land cover change history in the northwestern Great Plains ecoregion was characterized by conversions between cropland and grassland from 1972 to 2001. The rate of conversion from cropland to grassland increased due to the introduction of CRP since 1986 in the four state areas in the ecoregion. Conversion of grassland to cropland was a dominant driving factor responsible for C sources, and the recovery of grass cover from cultivated lands enhanced SOC sinks, but the magnitude of sequestration may depend on specific management measures. With the exception of a few locations where cropland was prevalent, the northwestern Great Plains was a consistent C sink, and SOC dynamics in the terrestrial ecosystems were highly related to dominant land cover categories (either grassland or cropland) and proportions over the large multiland cover region.

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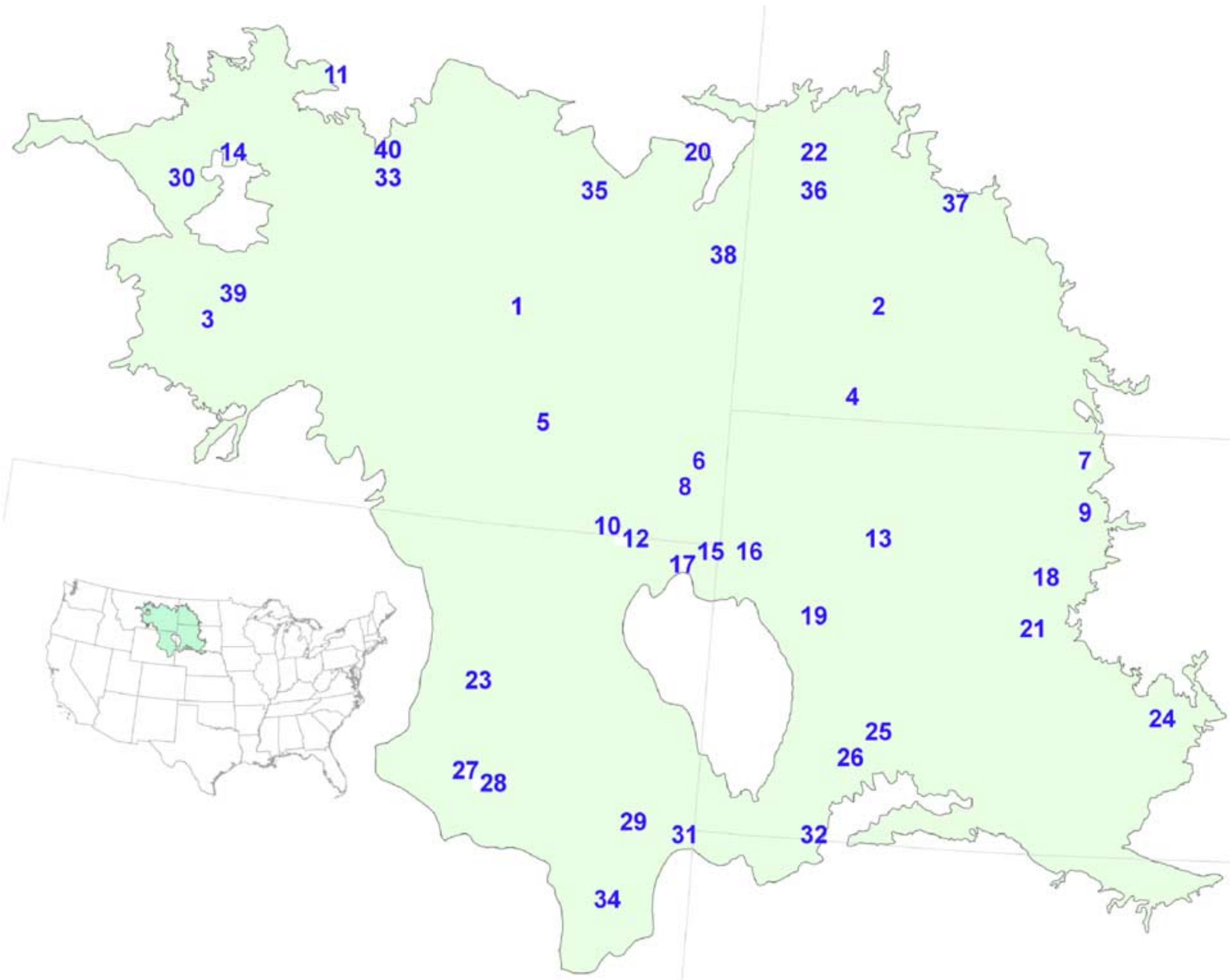

Figure 1. Study area and sample block locations in the Northwestern Great Plains ecoregion.

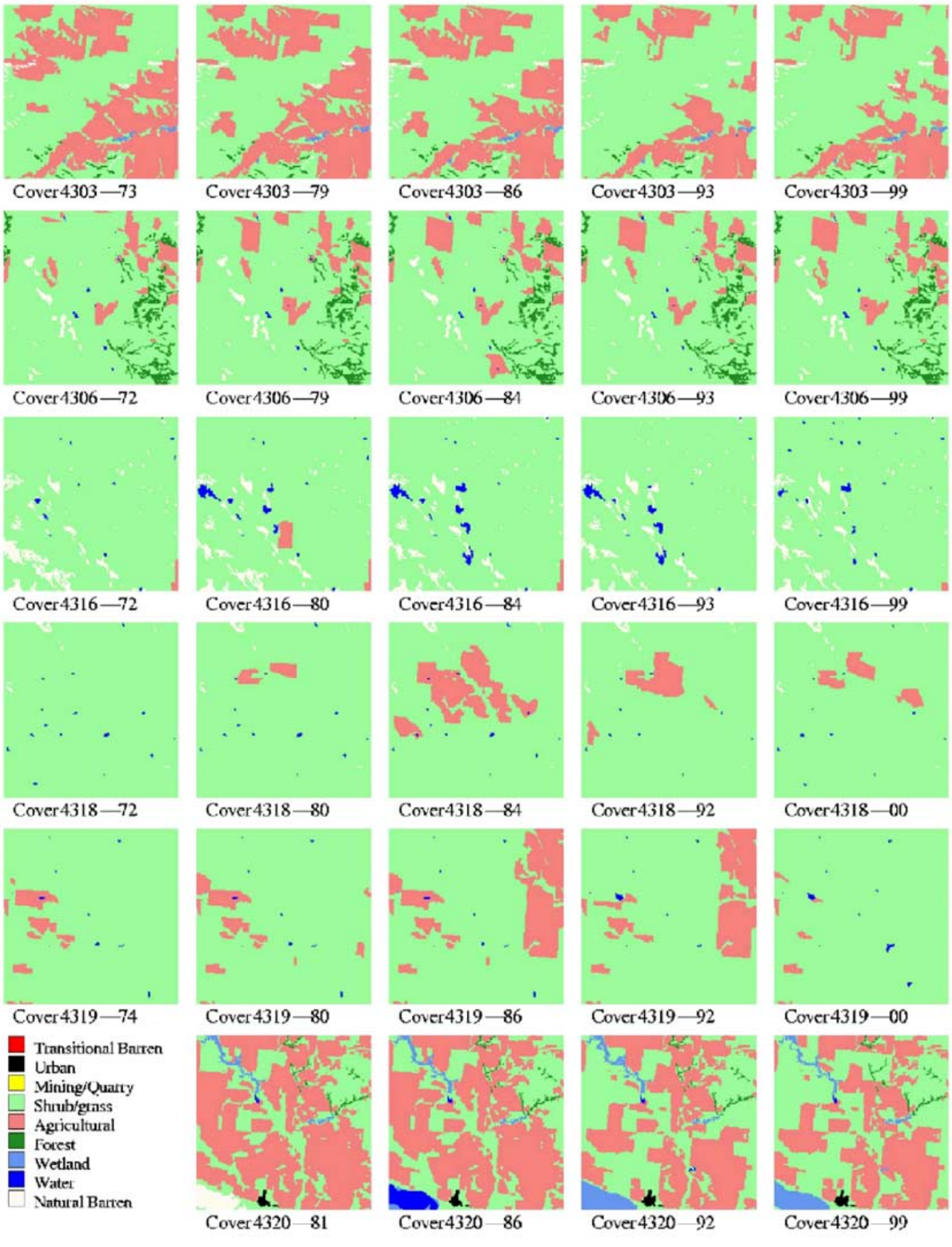

Figure 2. Spatial distribution patterns and temporal change trends for selected sample blocks (provided by the USGS Land Cover Trends Project team). Numbers below blocks denote block ID and year of imagery.

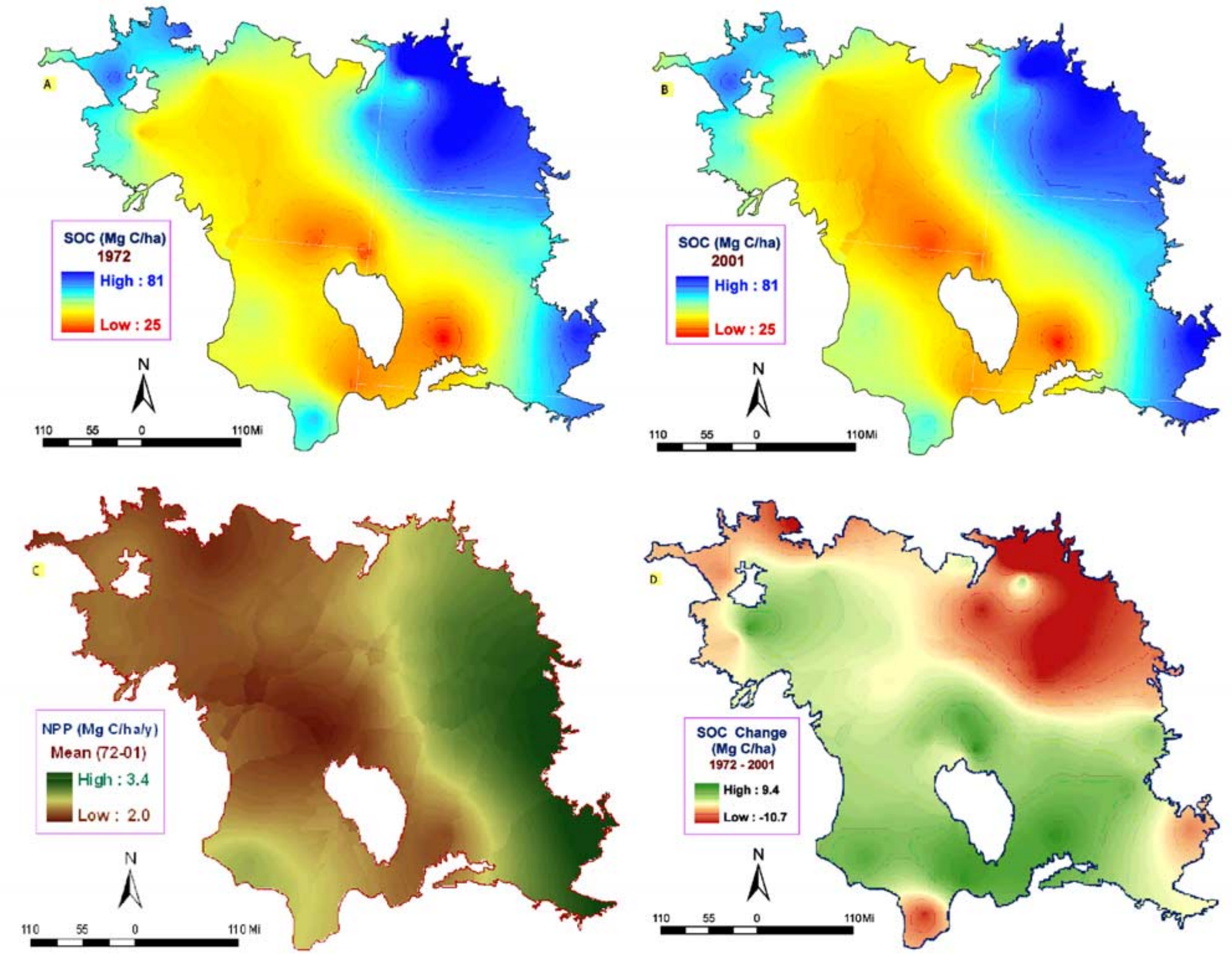

Figure 3. Spatial distribution patterns of SOC stocks, NPP, and SOC change in the ecoregion between 1972 and 2001: (a, b) the spatial distributions of total SOC stocks in 1972 and 2001, respectively; (c) the annual average net primary production (NPP) between 1972 and 2001; and (d) the change in SOC stocks from 1972 to 2001, and positive values indicate an increase in SOC stocks over this period).